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APPLICATION OF MONITORING TO SUBSTANTIATE THE BIOOLOGICAL METHOD OF SOIL RESTORATION DUE TO MILITARY OPERATIONS

As a result of military operations involving the use of various types of weapons in Ukraine, there is a significant negative impact on the environment: from the impact on the behavior and migration of fauna, which entails significant changes in natural ecosystems, to the multifaceted abiotic impact on the air, water and soil environments through various types of pollution (mechanical, chemical, noise, thermal, vibration, etc.).

The article highlights the problem of soil contamination in Ukraine as a result of military operations and identifies key factors of anthropogenic impact on the environment.

It also considers the main compounds and substances that enter the soil environment during combat operations and their potential negative impact on human health through the food chain. The aim of the article is to monitor bio- and phytoremediation methods, which are potential ways of restoring soils to a safe condition for further use in agriculture. The article provides a selection of plant species relevant to Ukraine for the purpose of removing specific pollutants that have entered the soil during military operations.

Key words: *military operations, soil contamination, war-caused pollutants, restoration of soil ecosystems, bioremediation, phytoremediation, environmental safety, safety of agricultural products.*

Introduction. In the modern world, as a result of excessive anthropogenic impact on the natural environment, its safety can already be questioned. Pollutants of various nature and chemical composition enter the environment as a result of human activity in completely different ways, where they can subsequently migrate and transform into other compounds, sometimes causing even greater damage than the original substance. The main and most powerful sources of pollution are emissions into the atmosphere from various industries, industrial and domestic wastewater discharges into water bodies, and agriculture, which pollutes the environment, especially the soil, in various ways: from the burial of dead livestock to the uncontrolled excessive use of fertilizers, pesticides and fungicides, which in high concentrations have a toxic, sometimes lethal, effect on flora and fauna that were not initially targeted for elimination..

The above activities are aimed at meeting human needs and are important economic and social components. Stopping anthropogenic impact on the environment means a complete cessation of human activity, which is a priori impossible. The negative impact caused by humanity can be minimized as much as possible by approaching the problem comprehensively, using the latest technologies and changing people's worldview and values, which should be nature centric.

However, in today's world, there are many gaps in the functioning of states as systems, not all states have equal rights in the global geopolitical arena, as a result of which the population suffers from poverty, hunger and wars.

Wars and armed conflicts have a large number of devastating consequences for the natural environment. These include the destruction of biodiversity, mass migration of species, mechanical changes to landscapes and soil degradation, additional vibration loads that can affect geological activity depending on the area, and direct environmental pollution. Among the types of pollution, we can highlight emissions from the combustion of fuel (both diesel and rocket fuel) and emissions resulting from the explosion of shells (including carbon dioxide and carbon monoxide, sulfur dioxide, and nitrogen oxides) [1], mechanical pollution of water bodies and soil with the remains of military vehicles, equipment, shells, debris from destroyed infrastructure, and chemical pollution with the contents of shells, petroleum products and spills of potentially hazardous substances as a result of damage to, for example, enterprises where such substances may be used or stored.

Considering that 70% of the territory of Ukraine consists of agricultural land [2], the issue of monitoring the quality of soil and products grown on damaged areas becomes extremely important. There are no legal requirements for mandatory monitoring of the quality of soil damaged by military action, but landowners should be responsible for the potential risks of contamination of agricultural products [3].

The greatest impact on agricultural land is in the frontline areas, as the density of explosive craters only increases over time due to regular shelling with various types of weapons of different calibers and chemical compositions [1]. Figures 1-6 show images of agricultural land attacked by various types of weapons. Soils throughout Ukraine are also suffering from long-range missile and drone strikes.

Purpose and task. The purpose of this article is to identify the most optimal methods for restoring soils damaged by military operations, in particular contamination by pollutants of various nature, in Ukraine, based on an analysis of scientific articles, reports by international organizations and international experience, using a comparative analysis of literature data.

Presentation of the main material research.

The main sources of heavy metals entering the soil during combat operations are damage to military equipment, the use of ammunition, fragments of shells, mines, aerial bombs, as well as combat waste generated by the destruction of infrastructure [4]. Some of the most dangerous metals are lead, copper, zinc, cadmium, nickel, chromium, and manganese [5]. The presence of heavy metals impairs the physical and chemical properties of the soil, reduces its fertility and inhibits the activity of soil microorganisms, which are key to maintaining the health of the ecosystem [4].

Excessive concentrations of heavy metals cause toxic effects on the development of vascular plants [6]. The content of heavy metals in agricultural soils can directly affect human health through the consumption of crops grown on contaminated soils [7].

In addition to heavy metals, petroleum product residues, which are constantly released into the environment during military operations, have a significant impact on the soil environment. The toxic effects of petroleum products on the human body can manifest themselves through the consumption of contaminated food grown in affected areas [8]. Petroleum products are represented by saturated and unsaturated hydrocarbons, aromatic hydrocarbons and resins. Polycyclic aromatic hydrocarbons (PAHs), which have carcinogenic and mutagenic properties, are particularly dangerous. Contamination with petroleum products has a significant impact on soil properties (water permeability, aeration capacity, mineral composition), which inhibits plant growth and development [9].

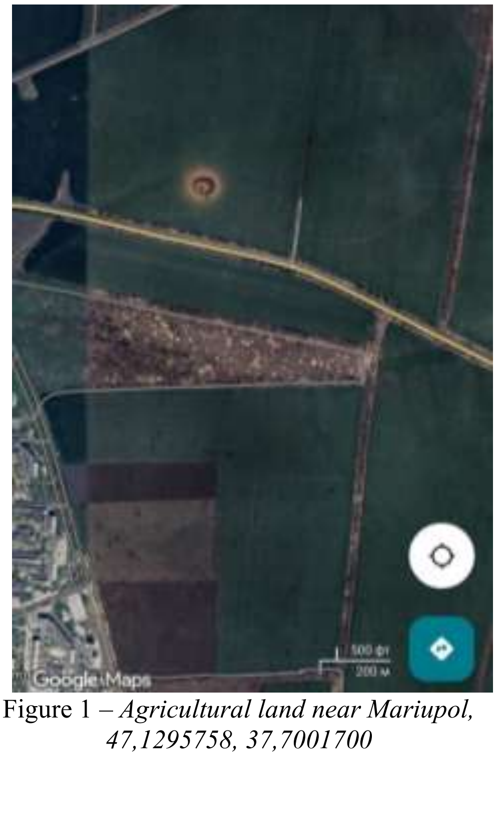

Figure 1 – *Agricultural land near Mariupol, 47,1295758, 37,7001700*

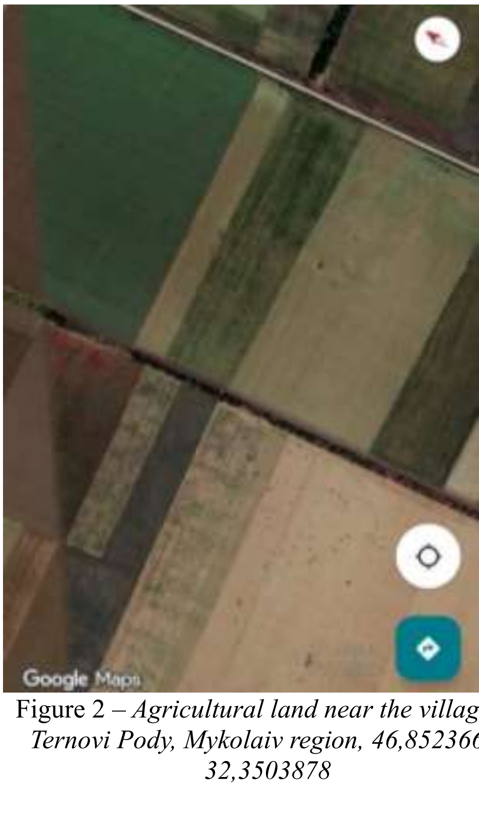

Figure 2 – *Agricultural land near the village of Ternovi Pody, Mykolaiv region, 46,8523664, 32,3503878*

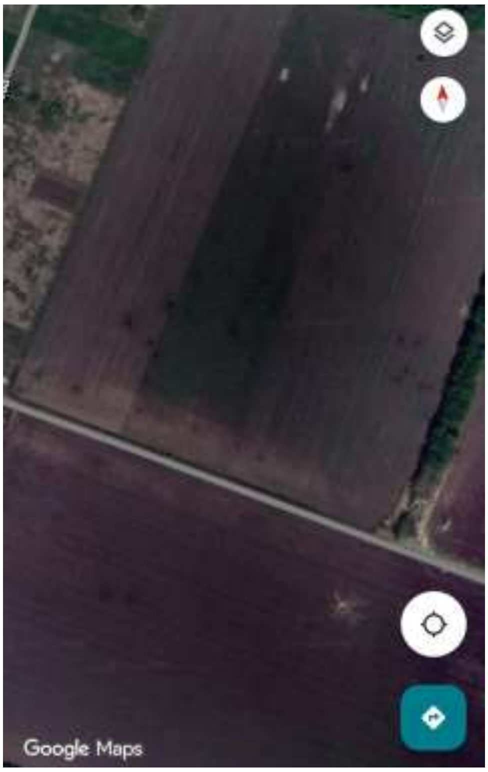

Figure 3 – *Agricultural land near the, village of Tsyrkuny, Kharkiv region, 50.080362,36.404144*

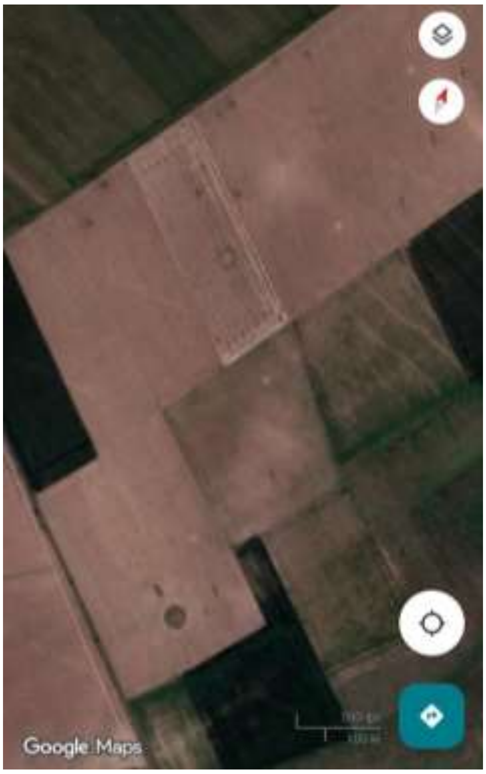

Figure 4 – *Agricultural land near the village of Synetskyi, Donetsk region, 48.945392,38.419409*

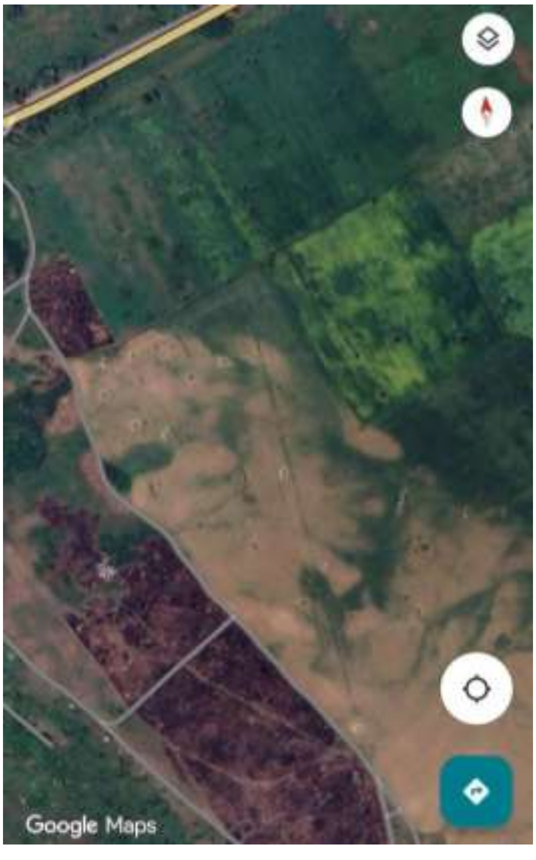

Figure 5 – *Agricultural land near the village of, Davydiv Brid, Kherson region, 47.250720,33.173254*

Figure 6 – *Agricultural land near the village of Avidivka, Odessa region, 46.032858,30.186393*

The activity of microorganisms is an essential component of healthy soil ecosystems. When a shell explodes, depending on the composition of the explosive, the temperature in the explosion cloud can vary from 2000 K to 4000 K [10]. At such temperatures, all organic matter that makes the soil fertile burns out, along with all microorganisms. The absence of microorganisms in the soil will potentially have a negative impact on the growth of plants used for phytoremediation. This issue requires additional research on the restoration of the soil microbiome to ensure favorable conditions for plant growth and the revival of the soil ecosystem.

One of the most promising methods of soil restoration in Ukraine is bioremediation. Biological restoration methods are environmentally friendly technologies for cleaning water, soil and even air from pollutants of various types and origins [11]. This approach involves the use of natural processes to remove various components from contaminated areas, which does not require significant financial costs**.**

Bioremediation involves the use of biological agents (mainly microorganisms: bacteria, fungi, algae) to decompose or remove unwanted components from the environment. The article 'Bioremediation an eco-friendly method for administration of environmental contaminants' [12] provides a comprehensive description of bioremediation techniques, including: bioaugmentation (the introduction of microorganisms to decompose pollutants), bioventing (the stimulation of aerobic microorganisms by pumping air), biosparging, biocomposting (mixing contaminated soil with organic waste to accelerate the decomposition of pesticides and petroleum products), and biopiles (aerated piles of contaminated soil). Biocomposting is the most promising and cost-effective method for soil remediation in Ukraine, especially due to the localized negative impact of events such as the explosion of a shell on a private plot of land used for agriculture

The above methods of bioremediation can be combined with phytoremediation, which in turn involves the use of plants and associated soil microorganisms to reduce the environmental impact of pollutants. The term phytoremediation itself comes from the Greek phyto – plant, remedium – to correct or remove evil [13].

The specific advantages of using phytoremediation as a method of soil restoration compared to traditional methods are increased biodiversity and fertility, and prevention of erosion [12], which are extremely important aspects, especially in the context of soil structure destruction and the extermination of microbial species diversity after an explosion.

In general, there are five main mechanisms for cleaning the environment of unwanted components [14]:

- phytoextraction - absorption of pollutants by roots and accumulation in the above-ground parts of plants (effective for metals);
- phytostabilisation is an immobilisation of pollutants in the soil through sorption, precipitation or complex formation in the inter-root space;
- phytodegradation is an enzymatic decomposition of certain organic compounds (herbicides, pesticides, petroleum products) into simpler ones with subsequent absorption by plants;
- rhizofiltration is a purification of water from metals by absorption by roots (effective for aquatic systems with low pollution);
- phytovolatilisation is a transformation of pollutants (such as mercury or arsenic) into volatile compounds and their removal through transpiration.

The table below shows the strengths and weaknesses of bio- and phytoremediation in the context of Ukraine.

Table 1 – Strengths and weaknesses of biological soil remediation methods

Method	**Advantages**	**Disadvantages**	**Prospects for application**
Bioremediation	Environmentally friendly, relatively inexpensive, can be used for organic contaminants	Significant duration of the process, need for monitoring	Restoration of small volumes of soil in local areas, including the private sector
Phytoremediation	Availability of plants, proven effectiveness, resistance to various types of pollutants	Significant duration, disposal of contaminated biomass, maintenance requirements, need for soil quality monitoring during the remediation process	Widespread use in agricultural areas

Species of plants used for phytoremediation.

Returning to issues relevant to Ukraine, namely the safety of agricultural soils, the most effective and economically acceptable mechanism would be classic phytoextraction. Sunflower (*Helianthus annuus L.*) is one of the most researched species for this process. It has high potential for phytoremediation, which has been confirmed in studies on the remediation of soils contaminated with nickel, lead, chromium and cadmium [15].

Studies have shown that sunflowers accumulate a higher concentration in its leaves, accounting for 55% of the total metal content compared to the stems. Another effective species is brown mustard or Indian mustard (*Brassica juncea*), which shows high potential for decontaminating lead-polluted soils, especially when using adjuvants such as EDTA, which chelate heavy metals, making them more available for absorption by plants [16]. In addition to these species, hybrid poplar (*Populus*) and dandelion (*Taraxacum officinale*) can be used for the phytoextraction of heavy metals such as chromium [17].

Phytoremediation allows plants to be used for the degradation of hydrocarbons, particularly thanks to their well-developed root system, which creates a favourable environment for symbiotic microorganisms in the rhizosphere. The uptake and absorption of organic chemical compounds depend on their physicochemical properties, in particular on the logarithm of the octanol-water partition coefficient ($logK_{ow}$). Chemicals with moderate hydrophobicity ($logK_{ow}$=1.0 – 3.5) are the most bioavailable to root vascular plants. However, some hydrophilic compounds, such as methyl tert-butyl ether, can also be absorbed by plants through water flow. [18].

For phytoremediation of oil-contaminated soils, *Bassia scoparia* is effective due to its associated rhizosphere microorganisms [19]. Alfalfa (*Medicago sativa*) can also significantly reduce the concentration of petroleum products in the soil [20]. Some ornamental plants, such as tall fescue (*Festuca arundinacea*) and birdsfoot trefoil (*Lotus corniculatus*), can be used to clean up oil-contaminated soils [21].

Hybrid poplar (*Populus*) can also be used to clean soil from explosives, in particular 2,4,6-trinitrotoluene (TNT), which is one of the main explosive components of most shells used to shell Ukrainian territory [22]. Studies have shown that poplars can absorb TNT from the soil, with most of the TNT being bound and transformed in the plant's root system. A summary table of plants for phytoremediation and corresponding pollutants is provided below.

Table 2 – Phytoremediation agents and pollutants against which they are effective

Plant	Type of pollutant	Features of use
*Helianthus annuu*s (sunflower)	Lead, cadmium, chromium, nickel	High accumulative capacity in leaves and stems
Brassica juncea (Indian mustard)	Lead (using chelates, in particular EDTA)	High level of Pb removal thanks to chelation
Populus spp. (hybrid poplar)	Heavy metals (Cr, Zn), explosives (TNT)	Active transformation of explosives in the root system
Taraxacum officinale (dandelion)	Chromium and other heavy metals	High adaptability in different conditions
Bassia scoparia (common broom)	Petroleum products, surfactants	Symbiosis with microorganisms increases the degradation of carbohydrates
Medicago sativa (alfalfa)	Petroleun products	Reduces the concentration of hydrocarbons in the soil
Festuca arundinacea (reed grass)	Petroleun products	Used for decorative recultivation
Lotus corniculatus (birdsfoot trefoil)	Petroleun products	Suitable for long-term ecosystem restoration

Fig. 7 shows the efficiency of metal absorption by various hyperaccumulator plants, including Indian mustard (*Brassica juncea*), galvanophilic fern (*Pteris vittata*), poplar (*Populus spp*.), annual sunflower (*Helianthus annuus*), and alpine penny-cress (*Noccaea caerulescens*, previously *Thlaspi caerulescens*), according to the article 'Exploring Phytoremediation And Plants As Natural Cleaners Of Polluted Environments' by Deborah Paripuranam et al., 2025 [11].

International experience in the use of phytoremediation.

In the field of heavy metals, phytostabilisation technology has been proven and is successfully used in both Europe and the United States [23]. For example, Belgium has conducted successful large-scale trials of zinc (Zn) and cadmium (Cd) immobilisation using additives and recultivation, while the US Environmental Protection Agency (EPA) has supported the use of biosludge for the recultivation of mining sites. A new direction is phytomining (extraction by plants) of valuable metals such as nickel, thallium and gold, where the main goal is cost-effective extraction, not just decontamination. However, the efficiency of phytoextraction of heavy metals, especially for meeting strict regulatory standards, remains low, as confirmed by studies in Denmark [24]. In a heavily contaminated site in Valby (Denmark) using willow (*Salix sp.*) and poplar (*Populus sp.*), the efficiency of Cd removal by willow was less than 0.5% over 10 years, and for other heavy metals, less than 1‰ over 10 years. Calculations have shown that it could take more than 178,360 years for poplar to meet the standards for nickel (Ni). Despite this, planting trees on contaminated sites is still recommended due to additional benefits: reduced leaching, CO_2 fixation and habitat creation [24].

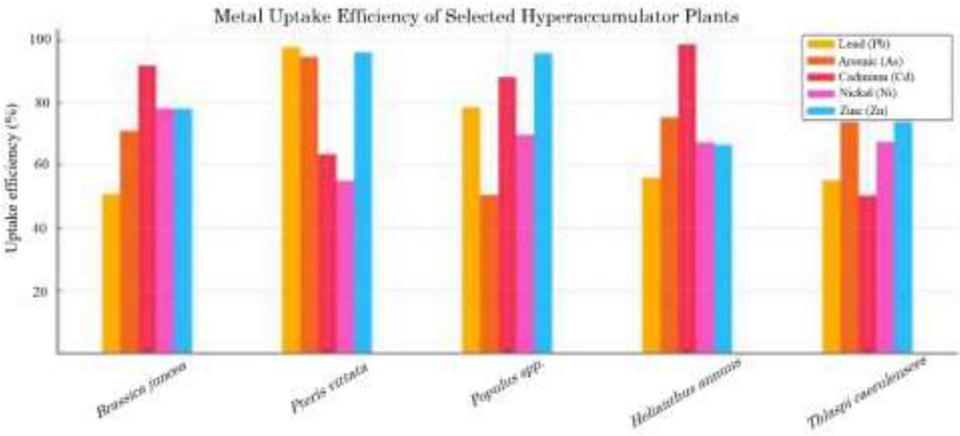

Figure 7 - *Efficiency of metal uptake by plants*

In Japan, *Thlaspi caerulescens* (Gang ecotype) has significant potential for phytoremediation of cadmium (Cd)-contaminated soils [25]. Compared to the slow extraction recorded in Denmark, studies on representative soils in Japan (fluvisol and andosol) have shown that only about 2 harvests for fluvisol and about 6 harvests for andosol may be needed to reduce the total Cd concentration by 50%. To increase the effectiveness of Cd phytoremediation in Japan, it is recommended to use short rotation (repeated harvesting and planting), as this increases the availability of Cd and uses new rhizosphere volume. Figure 8 shows the decreasing dependence of the total cadmium content in the soil on the number of harvests [25].

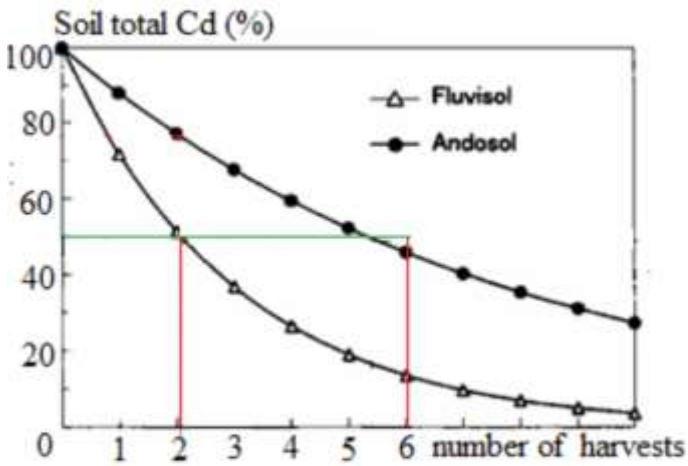

Figure 8 - *Dynamics of reduction of total Cd depending on the number of harvests*

In Italy (Treccate), following an oil well spill, agricultural crops such as maize (*Zea mays*) and sorghum (*Sorghum*) were significantly more effective in removing petroleum hydrocarbons than agronomic methods or natural attenuation [23]. In addition, pilot studies have shown that the remediation of soils contaminated with petroleum hydrocarbons (PHC) and trace elements (TE) using plants (*L. sativum, M. sativa, H. annus*) and additional microorganisms and earthworms, demonstrated a reduction in PHC content by 80% and metals by 20% after 17 months [26].

The Baltic Phytoremediation concept, implemented as a cross-border project between Sweden, Poland and Lithuania, aims to use phytoextraction in combination with biomass generation and its subsequent use as an energy resource. Thus, after burning contaminated plant biomass, valuable ash can be recovered for further use. This approach increases energy efficiency and is an alternative energy source that reduces CO_2 emissions. Pilot cases for this project include reducing the level of nutrients (nitrogen and phosphorus) in landfill layers in Sweden, assessing the potential of energy crops to accumulate heavy metals (Zn, Cu, Cr, Pb, Ni and Cd) using sewage sludge as fertiliser in Lithuania, and phytoremediation of landfill leachate and soil remediation from heavy metals and organic pollutants (surfactants, dioxins, PCBs) in Poland [26].

With regard to radionuclides, although this area is less well documented, Phytotech conducted a field trial in the Chernobyl Nuclear Power Plant zone (Ukraine) using sunflowers on rafts to dramatically reduce 137Cs levels in surface water within 4–8 weeks. In addition, laboratory studies in the United States have shown that willow, *Kochia scoparia* and *Brassica napus* can remove 40–60% of 137Cs from soil under greenhouse conditions [23].

Management of post-phytoremediation biomass. After successful phytoremediation of the soil, a critically important task arises regarding the safe handling of the resulting biomass, which is contaminated with various compounds. Due to the presence of toxic pollutants, this biomass cannot be used as animal feed, compost or biofertiliser, as this would simply result in the transfer of pollutants within the environment, leading to repeated contamination and potential toxic effects on animals and plants. Therefore, the development and implementation of a sustainable strategy for managing this biomass is a key final stage in the entire process of soil restoration by phytoremediation.

According to Santanu Mukherjee's article ‘Sustainable management of post-phytoremediation biomass’ [27], this biomass is a ‘green concentrate of pollutants’ that requires careful planning for its disposal. One of the main classical approaches is thermal conversion, which includes incineration and pyrolysis. Incineration is a simple and effective way to reduce the volume of biomass and destroy organic pollutants. However, heavy metals will not disappear using this method, but will be concentrated in ash, which will require treatment and disposal. Pyrolysis allows the production of biochar, which in this case will still contain heavy metals, but this raw material can be used as a non-renewable filter in various technological processes due to its high adsorption capacity.

Chemical treatment methods can also be used to extract and stabilise contaminants. According to the study ‘Sustainable management of post-phytoremediation biomass,’ one of the most innovative areas is phyto-extraction, which involves the extraction of valuable metals from biomass. Chemical extraction of metals from biomass using acid solutions allows for the production of a concentrated solution from which metals can be recovered.

Conclusions

The article provides a comprehensive analysis of the problem of soil contamination in Ukraine as a result of military operations, in particular with heavy metals, petroleum products and explosives. The resulting soil degradation poses a threat to the environment and public health, as the bioaccumulation of certain pollutants and their toxic effects create a risk of contamination of agricultural products.

Based on literary sources and the experience of other countries, the effectiveness of bio- and phytoremediation is justified as the most promising and realistic method of soil restoration in Ukraine. Bioremediation, through the use of microorganisms, ensures the decomposition of organic pollutants and the restoration of the soil microbiome, while phytoremediation allows for the effective accumulation, transformation or immobilisation of heavy metals, hydrocarbons and explosives. Special attention should be paid to the use of hyperaccumulative plants such as common sunflower (*Helianthus annuus*), alfalfa (*Medicago sativa*) and Indian mustard (*Brassica juncea*), which are promising inexpensive options for restoring contaminated land. Poplars (*Populus spp*.) can also be used to prevent the spread of petroleum products in the environment and their toxic effects.

The results of the study prove that the use of bio- and phytoremediation methods is scientifically sound and practically feasible for the restoration of degraded soils in Ukraine. Based on the analysis, it is recommended to launch a national soil restoration program using these methods, integrating international experience and adapting it to Ukrainian realities.

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ЗАСТОСУВАННЯ МОНІТОРИНГУ ДЛЯ ОБҐРУНТУВАННЯ БІОЛОГІЧНОГО МЕТОДУ ВІДНОВЛЕННЯ ҐРУНТІВ ВНАСЛІДОК ВОЄННИХ ДІЙ

Внаслідок ведення бойових дій із застосуванням різних видів зброї в Україні здійснюється значний негативний вплив на навколишнє середовище. Він проявляється у багатьох формах: від порушення поведінки та міграційних маршрутів представників фауни, що призводить до трансформації природних екосистем, до масштабного абіотичного впливу на повітряне, водне та ґрунтове середовище через різні види забруднення (механічне, хімічне, шумове, теплове, вібраційне тощо). Особливої уваги заслуговує проблема забруднення ґрунтів, оскільки вони виконують роль природного депо токсичних речовин, які здатні мігрувати харчовими ланцюгами й прямо впливати на здоров'я людей.

У статті висвітлено актуальну проблему деградації ґрунтового покриву України внаслідок військових дій та визначено ключові антропогенні чинники, що посилюють негативні екологічні наслідки. Детально розглянуто основні сполуки та речовини, які потрапляють у ґрунти під час бойових дій: залишки вибухових речовин, важкі метали, паливно-мастильні матеріали, сполуки азоту, хлору та інші полютанти. Окремо акцентовано увагу на їх потенційному негативному впливі на біоту та на ризиках для здоров'я людей, які можуть виникати через накопичення цих токсикантів у продуктах харчування.

Метою дослідження є огляд сучасних методів біоремедіації та фіторемедіації, що розглядаються як перспективні технології для відновлення ґрунтів, приведення їх до екологічно безпечного стану та подальшого використання у сільському господарстві. У роботі наведено приклади застосування в Україні рослин-акумуляторів і гіпераккумуляторів, здатних видаляти специфічні полютанти (важкі метали, нафтопродукти, залишки вибухових речовин), які потрапили у ґрунт під час війни.

Запропонований підхід спрямований на комплексне відновлення довкілля, збереження біорізноманіття та мінімізацію екологічних ризиків для населення. Результати дослідження можуть стати підґрунтям для формування державних програм з екологічної реабілітації територій, постраждалих від бойових дій, а також для подальших міждисциплінарних досліджень у сфері екотехнологій, сталого розвитку та післявоєнної відбудови країни.

Ключові слова: *військові дії, забруднення ґрунтів, war-caused pollutants, відновлення ґрунтових екосистеми, біоремедіація, фіторемедіація, безпека довкілля, безпека сільськогосподарської продукції.*

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